How to Design System Grounding in Low Voltage Electrical Systems

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Evolution of system requirements

Commonly used system grounding types are:

- Exposed-conductive parts connected to neutral – TN;
- Grounded neutral – TT;
- Ungrounded (or impedance-grounded) neutral – IT;

The objective of these three grounding systems is identical regarding protection of people and equipment - mastery of insulation fault effects. They are considered to be the same with respect to safety of people against indirect contacts.

Nevertheless, the same is not necessarily correct for dependability of the low voltage electrical installation with respect to:

- System availability; and
- Maintenance requirements.

Quantities that can be calculated are subject to increasing requirements in factories and buildings. Also, the control and monitoring equipment in buildings (electrical power distribution management systems) has an increasingly crucial role in management and dependability. These developments in dependability requirements impact the selection and design of system grounding. It needs to be kept in mind that the issue with service continuity (keeping a sound network in public distribution by disconnecting consumers with insulation faults) played a role when system grounding first emerged.

Insulation Fault Causes

In order to provide staff protection and service continuity, conductors and live elements of electrical installations are "insulated" from the frames connected to the ground. Insulation is accomplished by:

- Applying insulating materials; and
- Distancing, which calls for clearances in gases (air, SF6) and creepage distances (concerning switchgear, for example, an insulator flash over path).

Insulation is described by set voltages which, in line with standards, are applied to new products and devices with:

- Lightning impulse withstand voltage (1.2; 50ms wave);
- Insulating voltage (highest network voltage); and
- Power frequency withstand voltage (2 U + 1,000 V/1mn).

Example for a LV type switchboard:
- Insulating voltage: 1,000 V
- Impulse voltage: 12 kV

When new equipment is manufactured as per adequate practices with products as specified in standards, the risk of insulation faults is extremely low. Nevertheless, as the installation ages this risk increases.

The installation is exposed to different aggressions which increase insulation faults. For instance:
- <u>During installation:</u>
    - Mechanical damage to an underground cable insulator
- <u>During service:</u>
    - Conductive dust
    - Insulator thermal ageing due to excessive temperature caused by too many cables in a cable duct, a poorly ventilated cubicle, climate, current or voltage harmonics, overcurrent, etc.
    - The electro-dynamic forces created during a short-circuit which may damage a cable or decrease a clearance
    - The operating and lightning overvoltage
    - The 60 Hz return overvoltage, created by an insulation fault in MV

Typically, it is a mix of these primary causes which creates the insulation fault. The latter is:
- Either of differential mode (between energized conductors) and becomes a short-circuit
- Or of common mode (between exposed conductors and frame or ground), a fault current then flows in the protective conductor (PE).
- LV system grounding is mainly concerned by common mode faults which mainly occur in loads and cables.

Accidents linked to insulation faults

An insulation fault, regardless of its cause, presents danger for:

- Preservation of property;
- Electrical power availability; and
- Personnel.

Electric Shock affecting People

A person exposed to an electrical voltage is electrified. This person may suffer from:

- muscular contraction;
- discomfort;
- burn; or
- Cardiac arrest (this is Electrocution) .

All of above effects are presented in Figure 1.

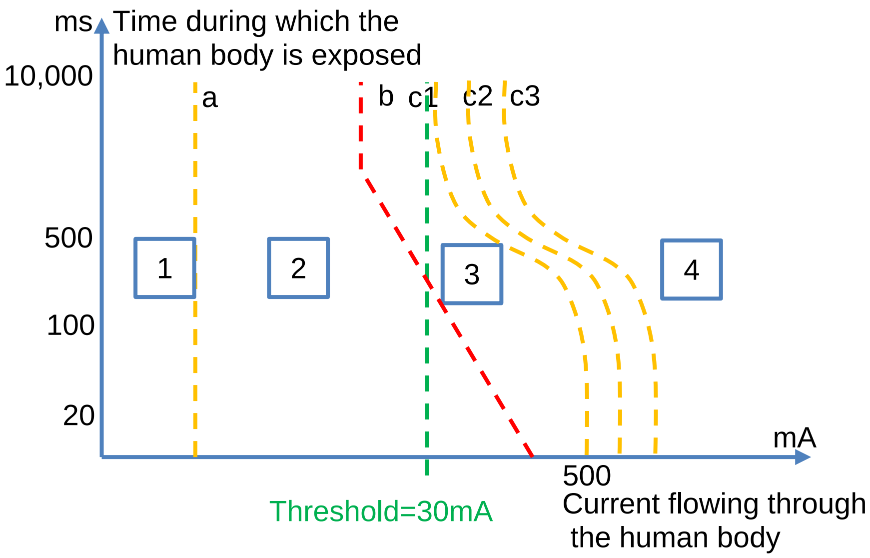


Figure 1. Time/current area of AC impact (15 Hz to 100 Hz) on people (defined as per IEC 60449-1)

Zone 1: Perception
Zone 2: Considerable discomfort
Zone 3: Muscular contractions
Zone 4: Risk of cardiac arrest

C2: Likelihood <5%
C3: Likelihood ≥50%

Since the protection of people against electric current lethal effects is a priority, electric shock is the first and most important hazard that needs to be assessed.

The current strength (expressed in amperes), flowing through the human body (especially the heart) is the most dangerous and can be fatal. In LV systems, body impedance value (skin resistance is one of the most important aspects of overall body impedance) changes according to environment including dry and wet premises and damp premises.

A safety voltage is defined as the maximum acceptable contact voltage for at least 5s and has been set at 50 V. In this case, there is a risk of contact voltage Uc surpassing 50 V voltage, which implies that the application time of the voltage needs to be limited and shortened by using different protection elements as presented in Table 1.

Table 1. Maximum safe contact voltage times

Dry or humid places: $U_L \leq 50$ V											
Presumed contact voltage (V)		<50	50	75	90	120	150	220	280	350	500
Protection devices maximum breaking time	AC	5	5	0.6	0.45	0.34	0.27	0.17	0.12	0.08	0.04
	DC	5	5	5	5	5	1	0.4	0.3	0.2	0.1
Wet places $U_L \leq 25$V											
Presumed contact voltage (V)		25	50	75	90	110	150	220	280		
Protection devices maximum breaking time	AC	5	0.48	0.3	0.25	0.18	0.1	0.02	0.02		
	DC	5	5	2	0.8	0.5	0.25	0.06	0.02		

Fire

Once it occurs, fire can have serious consequences for both personnel and property. Considerable number of fires are caused by localised temperature rises or an electric arc created by an insulation fault. The danger increases as the fault current rises. It also depends on the risk of fire or explosion that may happen in the premises.

Electrical power unavailability

It is increasingly important to master the issue of electrical power unavailability. In this case, the faulty element is automatically disconnected to clear the fault, the results may be:

- sudden absence of lighting

- switching off equipment for safety purposes;
- staff risk; and
- financial effect due to production loss.

This risk must be mastered in process industries, which are lengthy and costly to restart.

Also, if the fault current is high, it will can to:

- Damage that can be significant which increases repair costs and time; and

- Circulation of high fault currents in the common mode (between network and ground) which may create problem for sensitive equipment, especially if these are part of a "low current" system geographically distributed with galvanic links.

During de-energising, the occurrence of over-voltages and/or electromagnetic radiation processes may lead to malfunctioning of sensitive devices.

Direct and indirect contacts

Before studying the system grounding arrangements, definitions of direct and indirect contacts need to be provided.

- <u>Direct contact and protection actions</u>

This is an accidental contact of personnel with a live conductor (phase or neutral) or a normally live conductive element (as shown in Figure 2 (a)).

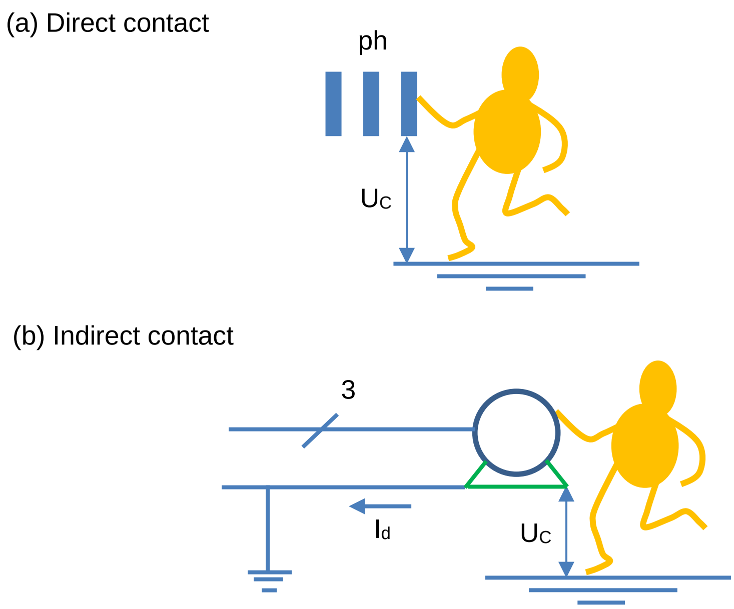


Figure 2. Direct and indirect contacts

In risky cases, the typical solution is by transferring electricity using a non-dangerous voltage, i.e. less than or equal to safety voltage. This is also known as using extra-low voltage. In LV, protection actions include placing live elements out of reach or insulating them by means of insulators, enclosures or barriers. Additional measure against direct contacts consists in using instantaneous 30 mA High Sensitivity Residual Current Devices known as HS-RCDs. Protection against direct contacts is totally independent from the system grounding, but this measure is mandatory in all circuit supply cases where implementation of the system grounding downstream is not mastered.

Contact of personnel with accidentally energised metal frames is known as indirect contact (as presented in Figure 2 (b)). Accidental energising is caused by an insulation fault. A fault current travels and creates a potential rise between the frame and the ground, therefore causing a fault voltage to appear which is dangerous, especially if it surpasses voltage U_L.
Installation standards have provided an official status for three grounding methods and defined the corresponding installation and protection practices. The protection actions against indirect contacts are based on grounding of the frames of loads and electrical equipment in order to prevent an insulation fault which actually represents a risk equivalent to direct contact.

Equipotentiality of simultaneously accessible frames

Interconnection of equipment frames helps in decreasing contact voltage. This is done by the protective conductor (PE) which connects the electrical equipment frames for entire buildings. If needed, they are supported by additional equipotential links (as presented in Figure 3).
It is important to remember that equipotentiality cannot be achieved in all points especially in single level premises. Therefore, for the study of system grounding and associated protection elements, the hypothesis Uc = Ud is used since Uc is the most equal to Ud. Uc and Ud are defined as:

- Ud – electrical device frame "fault" voltage, with respect to the deep ground, caused by an insulation fault
- Uc - contact voltage that depends on the potential Uc and the potential reference of the person exposed to the hazard

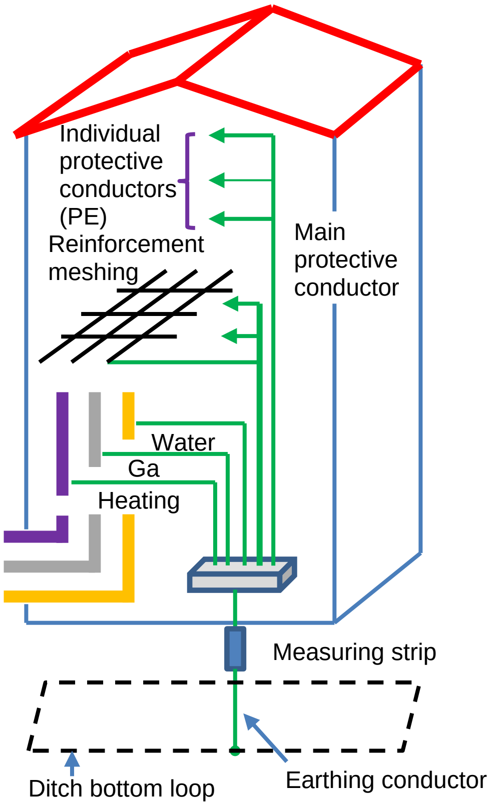


Figure 3. Equi-potentiality inside a building

Electrical hazard management

Electrical hazard management is based primarily on prevention. For example, by measuring a device's insulation before energising it, or by fault prediction based on live monitoring of insulation evolution of an unearthed installation (IT system).

In the case insulation fault happens, dangerous fault voltage must be removed by automatically disconnecting the section of the installation where this fault happened. Removal of the hazard depends on the system grounding.

System grounding and personnel protection

LV system grounding is defined by the grounding mode of the MV/LV transformer secondary and the method of grounding the installation frames. Therefore, identification of the system types is defined with 2 letters (as displayed in Figure 4):

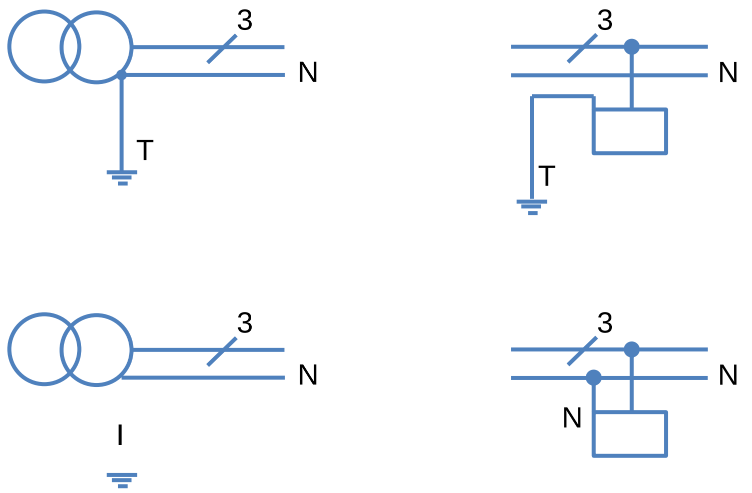


Figure 4. Connection arrangement of the neutral at the origin of the installation and of the frames of the electrical loads

- The first one for transformer neutral connection (2 options):
    - T for "connected" to the ground
    - I for "isolated" from the ground
- The second one for the type of frame connection (2 options):
    - T for "directly connected" to the ground
    - N for "connected to the neutral" at the origin of the installation, which is connected to the ground

Combination of these two letters gives three possible arrangements:
- TT: Transformer neutral grounded, and frame grounded
- TN: Transformer neutral grounded, frame connected to neutral
- IT: Unearthed transformer neutral, grounded frame

The TN system includes several sub-systems:
- TN-C: If the N and PE neutral conductors are one and the same (PEN)
- TN-S: If the N and PE neutral conductors are separate
- TN-C-S: Use of a TN-S downstream from a TN-C (the opposite is forbidden)

TN-S is mandatory for networks with conductors of a cross-section 10 mm2 Cu.
Each system earthing can be applied to an entire LV electrical installation. Nevertheless several system grounding arrangements may be used in the same installation, as shown in

Figure 5.

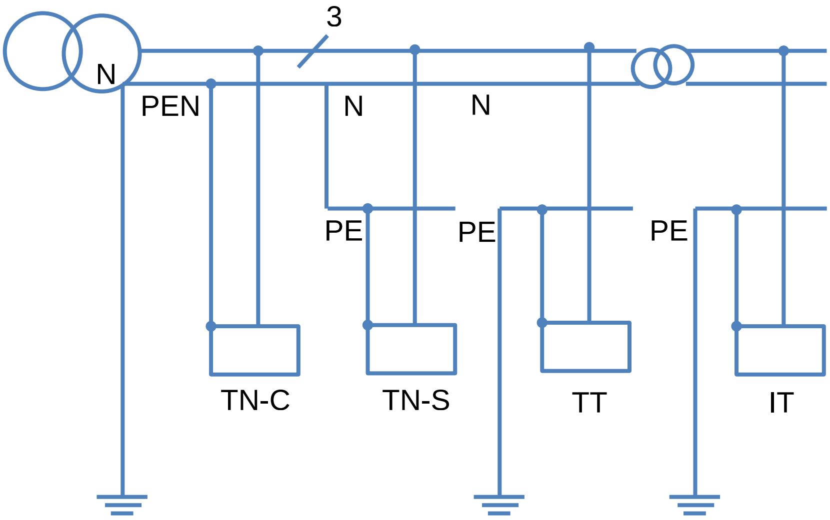


Figure 5. Example of the different system grounding arrangements included in the same LV installation

TN grounding system

In the case of TN grounding arrangement, the fault current I_d is only limited by the impedance of the fault loop cables (as shown in the Figure 6):

$$I_d = \frac{U_0}{R_{ph1} + R_d + R_{PE}}$$

For a feeder and as soon as R_d~0:

$$I_d = \frac{0.8U_0}{R_{ph1} + R_{PE}}$$

Once a short-circuit happens, impedances upstream from the relevant feeder cause a voltage drop of around 20 % on phase-to-neutral voltage Uo, which is the nominal voltage between phase and ground.

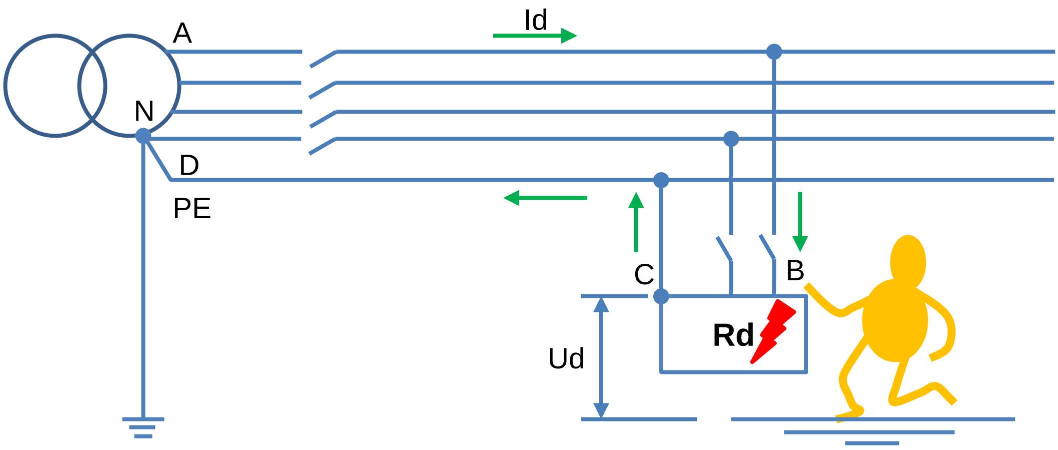


Figure 6. Fault current and voltage in TN grounding arrangement

$$U_d \approx \frac{0.8U_0}{2} \quad if \quad R_{PE} = R_{ph} \quad and \quad R_d = 0$$

$$I_d = \frac{U_0}{R_{AB} + R_d + R_{CD}} \rightarrow \frac{0.8U_0}{R_{ph} + R_{PE}}$$

Therefore, I_d induces a fault voltage with respect to ground:

$$U_d = R_{PE} \cdot I_d$$

$$i.e. \quad U_d = 0.8U_0 \frac{R_{PE}}{R_{ph1} + R_{PE}}$$

For LV networks, the voltage of around $U_0/2$ (if $R_{PE}=R_{ph}$) is dangerous since it surpasses the limit safety voltage, even in dry atmospheres (U_L=50 V). The installation or part of the installation must then be automatically and instantly disconnected, as shown in Table 2. Since the insulation fault resembles a phase-neutral short-circuit, breaking is accomplished by the Short-Circuit Protection Device (SCPD) with a maximum specified breaking time depending on U_L.

Table 2. Breaking time in TN grounded systems

U_0 (V) phase/neutral Voltage	Breaking time (s) U_L=50V	Breaking time (s) U_L=25V
127	0.8	0.35
230	0.4	0.2
400	0.2	0.05
>400	0.1	0.02

Implementation

To ensure that the protection device has been activated, the current I_d must be higher than the operating threshold of the protection device I_a ($I_d > I_a$) irrespective of the fault location. This condition must be checked at the installation design stage by assessing the fault currents for all the distribution circuits.

If the same path is occupied by the protective conductor - PE- and the live conductors, calculation will be simplified. To guarantee this situation, another approach consists in defining a maximum impedance value on the fault loops according to the type and rating of the selected SCPDs. This approach may result in increasing the cross-section of the live and/or protective conductors. Another method of checking that the element will ensure protection of personnel is to calculate the maximum length not to be surpassed by each feeder for a given protection threshold I_a.

To determine I_d and L_{max}, three techniques can be applied:

- The impedance technique
- The composition technique
- The conventional technique

The latter gives the following formula:

$$I_d = \frac{0.8U_0}{Z} = \frac{0.8U_0}{R_{ph} + R_{PE}} = \frac{0.8U_0 S_{ph}}{\rho(1+m)L}$$

For the protection element to complete its function properly, I_a must be lower than I_d. Therefore, the expression of L_{max}, the maximum length authorised by the protection device with a threshold I_a is:

$$L_{max} = \frac{0.8U_0 S_{ph}}{\rho(1+m)I_a}$$

Where:

- L_{max} = Maximum length in m;
- U_o = Phase-to-neutral voltage;
- ρ = Resistivity to normal operating temperature; and
- I_a = Automatic breaking current.

    - For a circuit-breaker $I_a = I_m$ (I_m operating current of the magnetic or short time delay trip release)

- For a fuse, current such that fuse total breaking time (prearcing time + arcing time) complies with values presented in Table 2.

If the line is longer than L_{max}, conductor cross-section must be increased. Alternatively, it must be protected with a Residual Current Device (RCD).

TT grounding system

When an insulation fault happens, the fault current I_d (shown in Figure 7) is limited by the ground resistances if the ground connection of the frames and the ground connection of the neutral are not associated. Assuming that R_d=0, the fault current is:

$$I_d \approx \frac{U_0}{R_a + R_b}$$

Fault current induces a fault voltage in the earth resistance:

$$U_d = R_a I_d \quad U_d = \frac{U_0 R_a}{R_a + R_b}$$

Since ground resistances are typically low and of the same magnitude, voltage of the order of $U_0/2$ is dangerous. Therefore, the part of the installation affected by the fault must be automatically disconnected (resistance of the frame earth connection is presented in Table 3).

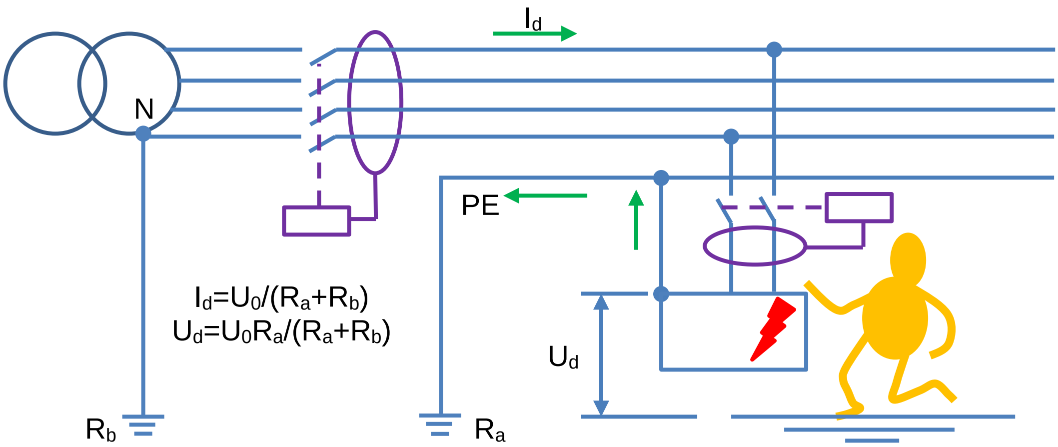


Figure 7. Fault current and voltage in TT grounding arrangement

Table 3. Upper limit of the resistance of the frame ground connection not to be surpassed according to RCD sensitivity and limit voltage

$I\Delta n \leq U_L/R_a$	Maximum resistance of ground connection	
	50 V	25 V
3 A	16 Ω	8 Ω
1 A	50 Ω	25 Ω
500 mA	100 Ω	50 Ω
300 mA	166 Ω	83 Ω
30 mA	1660 Ω	833 Ω

Implementation

Since the fault current (beyond which a risk is present (I_d=U_0R_{aL})) is far lower than the settings of the overcurrent protection devices, at least one RCD must be installed at the supply end of the installation. In order to increase electrical power availability, application of several RCDs ensures time and current discrimination on tripping. All these RCDs will have a nominal current threshold lower than I_{d0}.

De-energising by the RCDs must finish in less than 1 s. It is important to note that protection by RCD does not depend on cable length and authorises several separate R_a ground connections (which is an unsuitable measure since the PE is no longer a unique potential reference for the entire installation).

IT grounding system

The neutral is unearthed, i.e. not connected to the ground. The frame's ground connections are typically interconnected (just like the TN and TT grounding arrangements).

- In normal service (without insulation fault), the network is grounded by the network leakage impedance. Natural ground leakage impedance of a three phase 1 km long cable is characterised by the typical values:

  - C = 1 µF / km
  - R = 1 MΩ/ km

which give (in 60 Hz):

  - Zcf = 1 / j Cω= 2,652 Ω
  - Zrf = Rf = 1 MΩ,

Hence, $Z_f \approx$ Zcf = 2,652 Ω

In order to correctly set the potential of a network in IT grounding arrangement with respect to the ground, it is suggested that impedance (Zn ≈ 1,500 Ω) between transformer neutral and the ground is installed. If this is done, IT impedance-earthed system is formed.

Behaviour on the first fault

-Unearthed neutral:

The fault current is created as follows (maximum value in the case of a full fault and neutral not distributed).

$$I_f = I_{c1} + I_{c2}$$

Where:

$$I_{c1} = jCf\omega V_{13}$$

$$I_{c2}=jCf\omega V_{23}$$

$$I_d=U_{03}Cf\omega$$

For 1 km of LV network, the fault voltage will be equal to:

$$U_c=R_bI_d$$

Typically, this voltage is not dangerous and the installation can be kept in service. If the neutral is distributed, the shift of neutral potential with respect to the ground adds a current $I_{cn}=U_oC_f\omega$ and $I_d=U_o4Cf\omega$ (as shown in the Figure 8).

-Impedance-earthed neutral

First fault current is expressed as:

$$I_d = \frac{U}{Z_{eq}} \ where$$

$$\frac{1}{Z_{eeq}} = \frac{1}{Z_n} + 3jCf\omega$$

The corresponding fault voltage is still low and not dangerous. Installation can be kept in service. Even though risk-free continuity of service is a huge benefit, it is mandatory:

- to know that fault exists
- to track it and clear it quickly, before a second fault happens

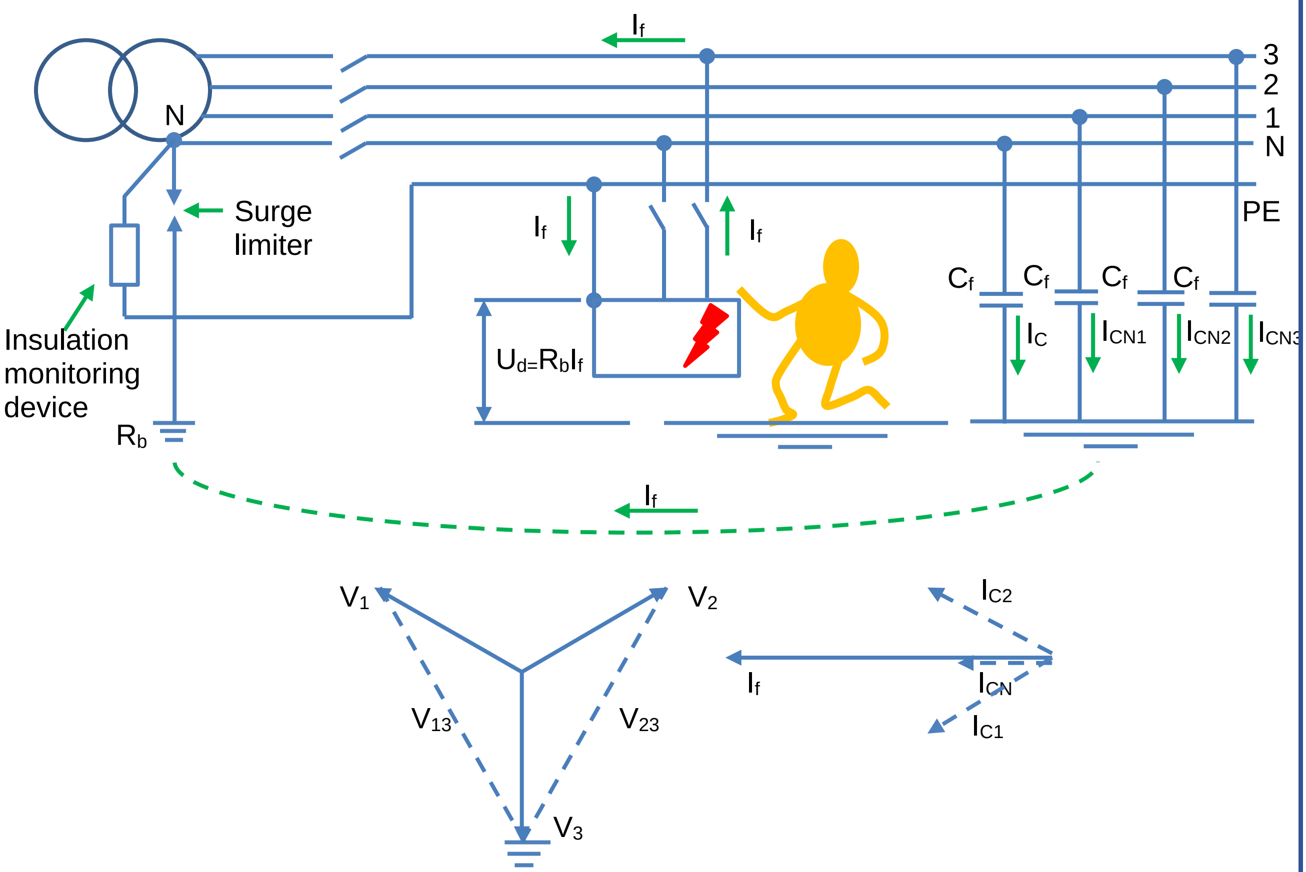


Figure 8. First insulation fault current in IT grounded system

In order to accomplish this, the below must be done:

- The fault information should be given by an Insulation Monitoring Device (IMD) which observes all live conductors, including the neutral
- the fault should be located using fault trackers

Behaviour on the second fault

When a second fault happens and the first fault has not yet been cleared, there are three options:

-The fault concerns the same live conductor: nothing happens and service can continue

-The fault concerns two different live conductors: if all frames are inter-connected, the double fault is a short-circuit (via the PE)

Electric shock hazard is similar to the one in TN system grounding arrangement. The most unfavourable conditions for the SCPDs (lowest I_d) are obtained when both faults happen on feeders with the same physical/electrical characteristics (cross-sections and lengths, as shown in Figure 9).

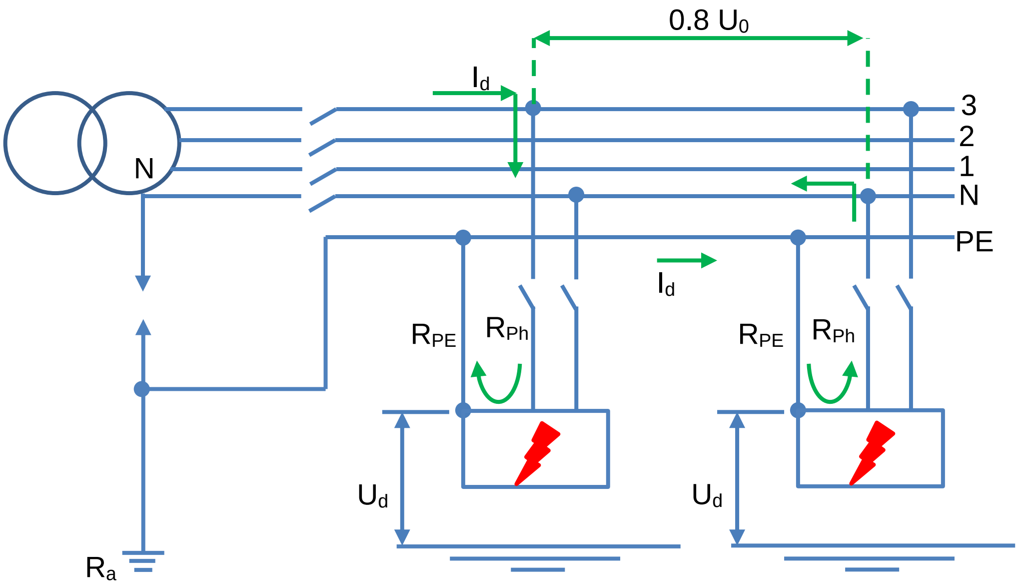


Figure 9. Second insulation fault current in IT grounding arrangement (distributed neutral) and feeders with the same cross-section and length

$$I_d \approx \frac{0.8\,U_0}{2\left(R_{PE} + R_{ph}\right)} \qquad U_d = \frac{0.8U_0}{2}$$

The SCPDs needs to be in line with following statements:

- In the case neutral is distributed and one of the two faulty conductors is the neutral

$$I_a \leq \frac{0.8U_0}{2Z}$$

- Or, in the case neutral is not distributed

$$I_a \leq \frac{0.8U_0\sqrt{3}}{2Z}$$

In this case one of the two faults is on the neutral, the fault current and fault voltage are twice as low as in the TN grounding arrangement. Due to this major manufacturers authorise longer SCPD operation times (as shown in Table 4). Just as in the TN system grounding, protection by SCPD is only applicable to maximum cable lengths:

- Distributed neutral:

$$L_{max} = \frac{1}{2}\frac{0.8U_0S_{ph}}{\rho(1+m)I_a}$$

- Non-distributed neutral:

$$L_{max} = \frac{\sqrt{3}}{2}\frac{0.8U_0S_{ph}}{\rho(1+m)I_a}$$

Table 4. Maximum breaking times specified in IT grounding arrangement

U_0/U (V) U_0: Phase/neutral voltage U:Phase to phase voltage	Breaking time (seconds)			
	U_L=50 V neutral not distributed	Neutral distributed	U_L=25 V neutral not distributed	Neutral distributed
127/220	0.8	5	0.4	1.00
230/400	0.4	0.8	0.2	0.5
400/690	0.2	0.4	0.06	0.2
580/1000	0.1	0.2	0.02	0.08

This is provided that the neutral is protected and its cross-section equal to phase cross-section. Due to this certain standards advise against distributing the neutral.

-Situation where all frames are not interconnected. For frames grounded individually or in groups, each circuit or group of circuits must be protected by a RCD.

In the case of an insulation fault in groups connected to two different grounding arrangements, the protective device's reaction to the insulation fault (I_d, U_d) is similar to that of a TT system (the fault current flows through the ground). Therefore, protection of personnel against indirect contacts is accomplished in the same way.

$$I\Delta n \leq \frac{U_L}{R_a}$$

Time discrimination can be achieved to give priority to continuity of operation on certain feeders.

In order to protect LV unearthed networks (IT) against voltage rises (arcing in the MV/LV transformer, accidental contact with a network of higher voltage, lightning on the MV network), a surge arrester needs to be placed between the neutral point of the MV/LV transformer and the ground (R_b).

Overview of the characteristics for different system grounding arrangements and relevant equations, with the main focus on personnel protection, is provided in Table 5.

Table 5. System earthing characteristics

		I_d	U_d	L_{max}	Continuity of operation
TN		$\frac{0.8U_0S_{ph}}{\rho(1+m)L}$	$\frac{0.8U_0}{1+m}$	$\frac{0.8U_0S_{ph}}{\rho(1+m)I_a}$	Vertical discrimination

TT		$\frac{U_0}{R_a + R_b}$	$\frac{U_0 R_a}{R_a + R_b}$	No constraint	Vertical discrimination
IT	1st fault	<1 A	$<<U_L$		No tripping
	Double fault with distributed neutral	$\leq \frac{1}{2}\frac{0.8U_0 S_{ph}}{\rho(1+m)L}$	$\leq \frac{m}{2}\frac{0.8U_0}{1+m}$	$\frac{1}{2}\frac{0.8U_0 S_{ph}}{\rho(1+m)I_a}$	Vertical discrimination and possibility of horizontal discrimination to the advantage of current feeders
	Double fault with non-distributed neutral	$\leq \frac{\sqrt{3}}{2}\frac{0.8U_0 S_{ph}}{\rho(1+m)L}$	$\leq \frac{m\sqrt{3}}{2}\frac{0.8U_0}{1+m}$	$\frac{\sqrt{3}}{2}\frac{0.8U_0 S_{ph}}{\rho(1+m)I_a}$	

PE cross-section that is typically equal to phase cross-section, can be half of phase cross-section when the latter exceeds 35mm2.

System grounding confronted with fire and electrical power unavailability hazards

Fire

It has been shown, that contact between a live conductor and a metal part can cause fire especially in vulnerable areas. This can happen when current exceeds 300 mA. These areas include:

- Premises with risk: Petrochemical factories, farms, etc.; and
- Premises with moderate risks, but where consequences may be extremely serious, e.g. very high buildings.

In the unearthed neutral grounding arrangement, the risk of "fire":

- is very small on the first fault; and
- is as important as in TN on the second fault.

For the TT and TN grounding arrangements, the fault current is dangerous considering developed power ($P=R_d I^2$):

- In TT = 5A < I_d < 50 A
- In TN = 1 kA < I_d < 100 kA

The power where the fault has happened is considerable, especially in the TN grounding arrangement, and fast action is crucial in order to limit the dissipated energy ($\int R_d i^2 dt$). Protection is provided by an instantaneous RCD with threshold of 300 mA, regardless of the system earthing arrangement.

When risk of fire is particularly high (manufacture/storage of inflammable materials, etc.), it is important to use a system earthing with earthed frames which naturally minimises this hazard (TT or IT). Please note that TN-C is forbidden in certain countries when a risk of fire and/or explosion is present, since PE and neutral conductors are one and the same, RCDs cannot be used.

Electrical power unavailability

This hazard is the most important for utility operators since it results in nonproduction and repair costs which can be considerable. It varies according to the selected system earthing. Availability (D) is a statistical quantity (as shown in Figure 10) equal to the ratio between two periods of time:

- Time during which the mains is present
- Reference time which is equal to the time "mains present + mains absent" Mean Down Time (MDT) also depends on the fault current and in particular on its strength which, according to its value, can cause:
- Damage of varying degrees to loads, cables, etc.
- Fire
- Malfunctioning on the low current control and monitoring devices

D – system availability

$$D = \frac{MUT}{MDT + MUT}$$

MUT – Mean Up Time – Mean failure free time
MDT – Mean Down Time (detection + repair + resumption of operation)

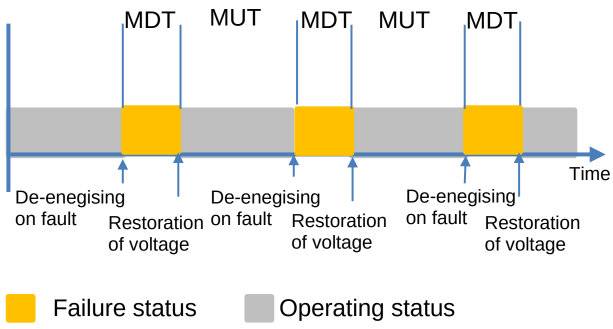


Figure 10. Electrical power availability

Therefore, system grounding must be examined in terms of electrical power availability, with special focus on the IT system earthing since it is the only one that authorises non-tripping in the presence of a fault.

In order to keep the advantage of IT system earthing, i.e. not interrupting electrical distribution on the first fault, the second fault must be prevented. Otherwise, it presents the same high risks as the TN grounding system. Therefore, the first fault must be cleared before a second fault happens. The use of efficient detection and locating techniques and availability of a maintenance team considerably decreases the chances for the "double fault". Also, monitoring devices are available and they monitor processes in insulation of the different feeders, provide fault prediction and anticipate status of the fault.This ensures maximum availability with the IT system earthing arrangement.

- The TN and TT system earthing arrangements

These grounding arrangements use discrimination on tripping. In TN system, this is accomplished with short-circuit protection elements if the installation protection plan has been properly implemented (discrimination by current and duration selectivity). In TT system, discrimination on tripping is simple to implement thanks to the RCDs which ensure current and time discrimination. In TN system, repair time according to $\int i^2 dt$, may be longer than in TT system, which also affects availability.

-All grounding arrangements

It is useful to anticipate insulation faults, especially on certain motors before startup. 20% of motor failures occur due to insulation faults which happen on energising. Insulation loss, on a hot motor cooling down in a damp atmosphere, degenerates into a full fault on restarting, causing significant damage to windings and production loss and even bigger risks if the motor has a safety function (drainage, fire, etc.). This type of problem can be avoided, regardless of the system earthing, by installing an Insulation Monitoring Device. If a fault happens, start-up is stopped. In conclusion, in terms of electrical power availability, the system grounding arrangements can be listed in the following order of preference: IT, TT, TN.

Note: In order to ensure continuity of operation, installation is equipped with a generator set or a UPS (Uninterruptible Power Supply). In that case there is a risk of failure to operate or a risk of delayed operation of the SCPDs. This happens during source changeover (lowest I_{sc} as shown in Figure 11). In TN and IT earthing arrangements, it is vital to verify that the protection conditions are always met (operating time and threshold), particularly for very long feeders. If this is not achieved, RCDs must be used.

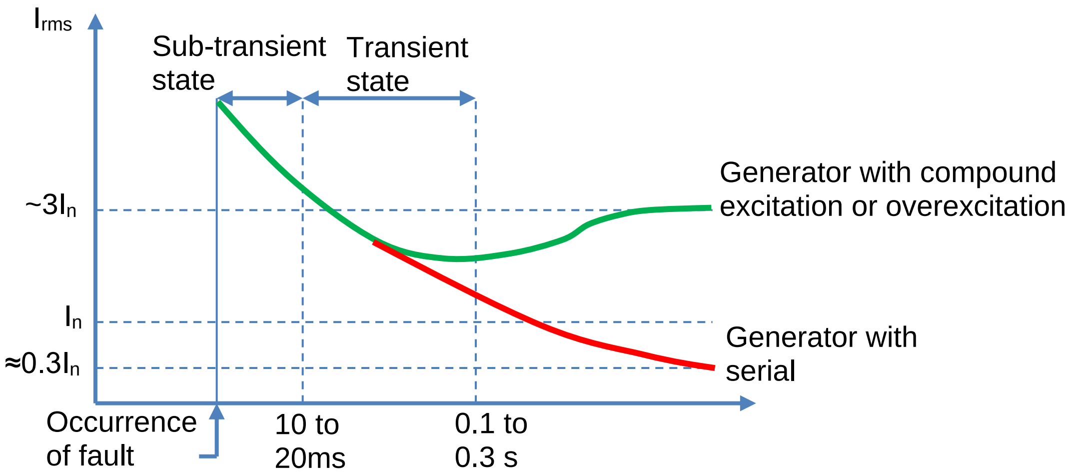


Figure 11. Short-circuit in a network supplied by a diesel standby generator

Influences of MV network on LV network, in terms of system earthing

LV networks, unless a replacement uninterruptible power supply (with galvanic insulation) or a LV/LV transformer is used, are affected by MV networks. This impact is reflected as:

- Capacitive coupling: Transmission of overvoltage from MV windings to LV windings
- Galvanic coupling: disruptive breakdown happen between the MV and LV windings
- Common impedance: if different ground connections are connected and a MV current flows off to ground. This results in LV disturbances, typically over-voltages, whose generating phenomena are MV incidents:
    - Lightning
    - Operating over-voltages
    - MV-LV disruptive breakdown inside the transformer
    - MV-frame disruptive breakdown inside the transformer

Typically this results in destruction of LV insulators with the resulting risks of harming people and destroying equipment.

Lightning

In the case MV network consists of overhead lines, lightning arresters are installed to limit the effects of a direct or an indirect lightning stroke. They are installed on the last pylon before the MV/LV substation and they limit overvoltage and direct lightning current to earth. However, a lightning wave is transmitted by capacitive effect between the transformer windings, to the LV live conductors and can rise up to 10 kV. Even though it is progressively weakened by the stray capacities of the network, it is suggested to install surge limiters (lightning arresters) at the origin of the LV network, regardless of the used earthing system (see Figure 12).

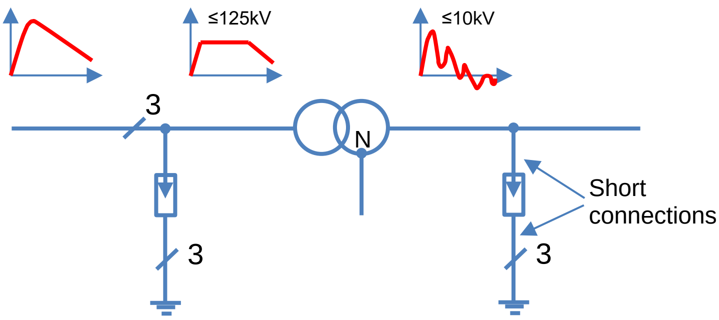


Figure 12. Transmission of lighting over-voltages (regardless of the neutral point earthing method, there are common over-voltages on phases)

Similarly, to prevent coupling by common impedance, it is wise never to connect the following to the ground connection of the LV neutral:

- MV lightning arresters
- Lightning rods placed on the roof of buildings. As a matter of fact, the lightning current would cause a rise in potential of the PE and/or the LV neutral (risk of disruptive breakdown by return) and loss of ground connection effectiveness.

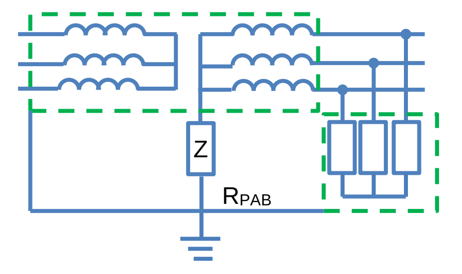
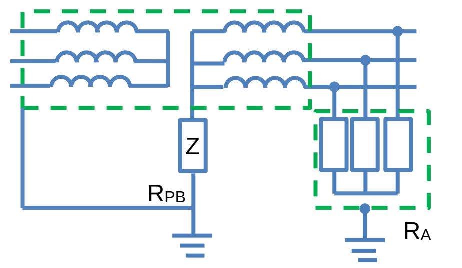
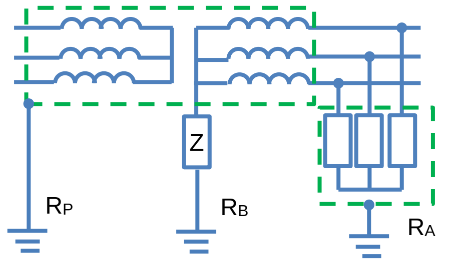
Operating over-voltages

Certain MV switchgear types (e.g. vacuum circuit-breakers) cause considerable over-voltages when operated. Unlike lightning which is a common mode disturbance (between network and ground), these over-voltages are, in LV, differential mode disturbances (between live conductors). These disturbances are transmitted to the LV network by capacitive and magnetic coupling. Just like all differential mode phenomena, operating over-voltages do not interfere, or only very slightly, with any of the system grounding.

MV transformer’s frame disruptive breakdown

On MV-frame disruptive breakdown inside the transformer and when the transformer frame and LV installation neutral are connected to the same ground connection, a MV "zero sequence" current (whose magnitude depends on the MV system grounding) can raise the transformer’s frame and neutral to a dangerous potential. Actually, the value of the transformer ground connection directly affects the contact voltage in the substation and dielectric withstand voltage of the LV equipment in the substation (in the case the LV neutral ground is separate from the substation one). Substation ground and LV neutral connections are not generally connected. However, if they are, a limit is set to the common ground connection value to prevent potential rise of the LV network. Typical earth connection values are presented in Table 6.

Table 6. Maximum resistance of the earth connection of the substation frames depending on the network system grounding

<table>
<tr>
<td>TNR or ITR (1)</td>
<td>
</td>
<td><table><tr><td>I_h (A)</td><td>$R_{PAB}(\Omega)$</td></tr><tr><td>300</td><td>3 to 20</td></tr><tr><td>1000</td><td>1 to 10</td></tr></table></td>
<td rowspan="3">Z: Direct earthing (Z=0) in TN and TT impedance-earthed or unearthed in IT.
I_{hMV}: Maximum strength of the first earth single-phase fault current of the high voltage network
U_{tp}: Power frequency withstand voltage of the low voltage equipment of the substation.
(1)The third letter of the system earthing means:
- All the frames are linked R
- The substation frame is connected to the neutral frame: N
- The earth connections are separated: S
Note: No values stipulated but these values prevent excessive potential rise of the assembly</td>
</tr>
<tr>
<td>TTN or ITN (1)</td>
<td>
</td>
<td><table><tr><td>I_{hMV} (A)</td><td>$R_{PB}(\Omega)$</td></tr><tr><td>300</td><td>3</td></tr><tr><td>1000</td><td>1</td></tr></table></td>
</tr>
<tr>
<td>TTS or ITS (1)</td>
<td>
</td>
<td><table><tr><td>Utp (kV)</td><td>2</td><td>4</td><td>10</td></tr><tr><td colspan="4">I_{hMV} (A) $R_P(\Omega)$</td></tr><tr><td>300</td><td>4</td><td>8</td><td>20</td></tr><tr><td>1000</td><td>1</td><td>3</td><td>10</td></tr></table></td>
</tr>
</table>

The maximum value allowed for the ground connection resistance depends on the equi-potentiality conditions of the frames of the LV network (its system grounding).

MV-LV disruptive breakdown inside the transformer

LV network must be earthed to prevent the rising of LV network potential to the phase-to-neutral voltage of the MV network in the case of MV-LV disruptive transformer breakdown. The consequences of this fault are:

- In TN earthing system the complete LV network, including the PE, is exposed to voltage

$Ih_{MV}R_{PAB}$ or $Ih_{MV}R_{AB}$.

In the case this overvoltage surpasses the dielectric withstand of the LV network (in reality the order of 1,500 V), LV disruptive breakdowns are possible if the equi-potentiality of all the frames, electrical or not, of the building is not properly done or incomplete.

- In the case of the TT earthing system the load frames are at the potential of the deep ground. Complete LV network is exposed to $Ih_{MV}R_{PB}$ or $Ih_{MV}R_B$. There is a risk of disruptive breakdown "by return" of loads if the voltage generated in RPB or RB surpasses their dielectric capability.

- In the case of IT system grounding a discharger, short-circuits itself as soon as its arcing voltage is reached. Consequently, it translates the problem to the level of the TN earthed network (or TT network in the case there are several ground connections).

In any case, MV/LV disruptive faults can be severe, both for the LV installation and loads, especially if LV neutral ground connection is not controlled.

Figure 13 presents an example of overhead public distribution. Risks of lightning, operating overvoltage and transformer frame-MV and MV-LV disruptive failures are shown.

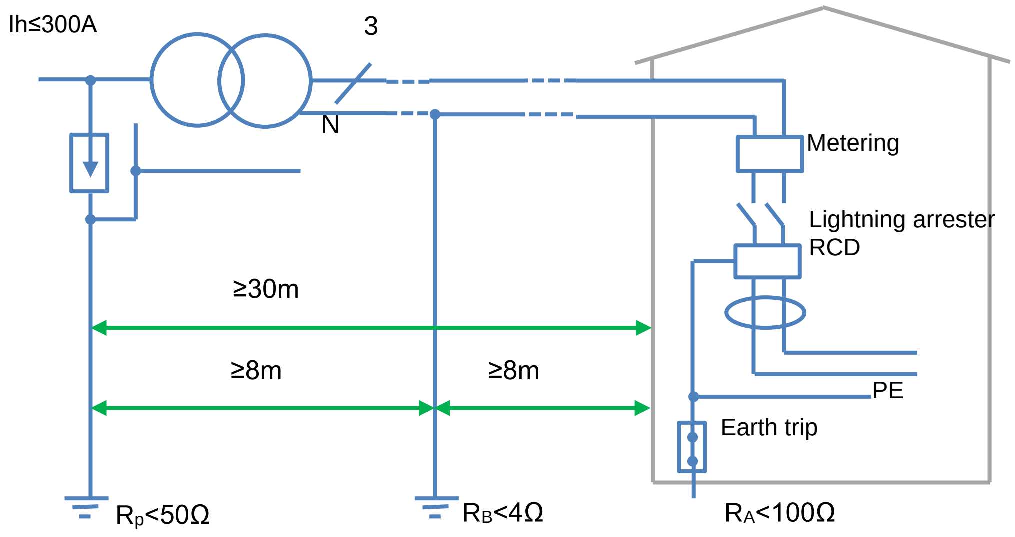


Figure 13. Typical overhead public distribution

Figure 13 indicates that equi-potentiality of the complete distribution (all MV frames, neutrals and connected application frames) is not crucial. Each risk is separately treated.

Switchgear and selection of system grounding

Selection of system grounding affects switchgear type and its installation.

TN grounding system

In TN grounding system the SCPDs (circuit-breaker or fuses) provide protection against insulation faults, with automatic tripping according to a specified maximum breaking time.
- Circuit-breaker tripping happens at a level defined by the type of the tripping release (as shown in Table 7).

Table 7. LV circuit-breakers tripping current (magnetic or short time delay)

	Trip release type	Operating threshold
Household (EN 60898)	B	$3I_n \leq I_a \leq 5I_n$
	C	$5I_n \leq I_a \leq 10I_n$
	D	$10I_n \leq I_a \leq 20I_n$
Industrial (IEC 60947-2)	G (low threshold)	$2I_n \leq I_a \leq 5I_n$
	D	$5I_n \leq I_a \leq 10I_n$
	MA (for motor starter)	$6.3I_n \leq I_a \leq 12.5I_n$

As soon as the fault current surpasses the threshold of the short-circuit protection trip release (typically "instantaneous"), opening starts in a time far shorter than defined maximum breaking time, for example 5 s for distribution circuits and 0.4 s for terminal circuits. When source and cable impedances are high, low threshold trip releases must be used. Alternatively, RCDs associated with the SCPDs need to be installed. These RCDs may be separate residual current elements or be combined with circuit-breakers (residual current circuit breakers) of low sensitivity. Their threshold needs to be:

$$I\Delta n < \frac{0.8U_0}{R_{ph} + R_{pe}}$$

Installation of a RCD makes loop impedance checking unnecessary, a fact which is of considerable importance when the installation is modified or extended. This solution cannot be applied with a TN-C type system grounding (the protective conductor is the same as the neutral one).
- Fuses used for short-circuit protection have time/current characteristics similar to the one

shown in Table 8. Individual validation of the ratings provided for each protection element is needed to check suitability of the maximum breaking time. If they are not suitable, fault loop impedance must be decreased (increase cable cross-section). Alternatively, fuse must be replaced with a low threshold or a residual current circuit-breaker.

Table 8. Typical fuse operating threshold limits

In gG (A)	Imin. 10 s	Imax. 5s	Imin 0.1 s	Imax 0.1 s
63	160	320	450	820
80	215	425	610	110
100	290	580	820	1450

TT grounding system

With TT grounding system, the small value of the fault currents does not allow the SCPDs to protect people against indirect contacts. RCDs need to be used in a combination with circuit-breakers or switches. RCD functional diagram is shown in Figure 14.

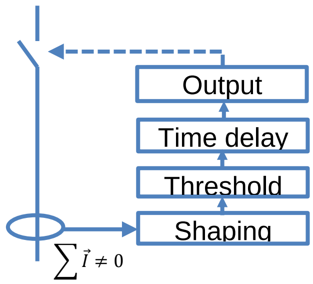


Figure 14. RCD functional diagram

Their implementation must meet following requirements:

- People protection, i.e.
    - Threshold $I\Delta n \leq U_L/R_A$
    - Breaking time ≤ 1s
- Continuity of service with thresholds and time delays allowing current and time discrimination
- Fire protection with $I\Delta n \leq 300$ mA

IT grounding system

In the case of a double fault, people safety is provided by the SCPDs. When the first insulation fault happens, the calculation proved there was no risk (contact voltage lower than limit safety voltage). Therefore, automatic de-energising is mandatory. This is the main benefit of this grounding system. To keep this advantage, standards suggest the application of an Insulation Monitoring Device (IMD) and locating the first fault. In the case a second fault happens, automatic breaking is important due to the electric shock risk. This is accomplished by SCPDs backed up by the RCDs if needed. Locating the first fault for repairs is simplified with the application of a Ground Fault Location Device (GFLD). Predictive maintenance, based on the monitoring of changes in insulation impedance, is also done. LV networks that use IT grounding system, which starts at a MV/ LV transformer, must be protected against risks of insulation faults between MV and LV by installing a "surge limiter".

Finally, to fix the potential of the LV network with respect to the ground (short network supplied by a MV/LV transformer), impedance can be installed between the transformer neutral and the ground. Its value of approximately 1,500 Ω (60 Hz) is very high in DC and in very low frequency so it does not obstruct insulation measurement and fault locating.

- IMD operating principle - A circuit fault results in a drop in insulation, or more precisely in resistance of the network. Therefore, the purpose of the IMDs is to monitor resistance value. Typically, they operate by injecting an AC or DC current between the network and the ground and by measuring the value of this current (as shown in Figure 15).

DC current injection provides permanent information of network insulation resistance. If this resistance decreases below a predetermined value, then the IMD signals the fault. Low frequency AC current injection (F ≈ a few hertz) monitors fault resistance but with a distortion due to the presence of network leakage capacitance.

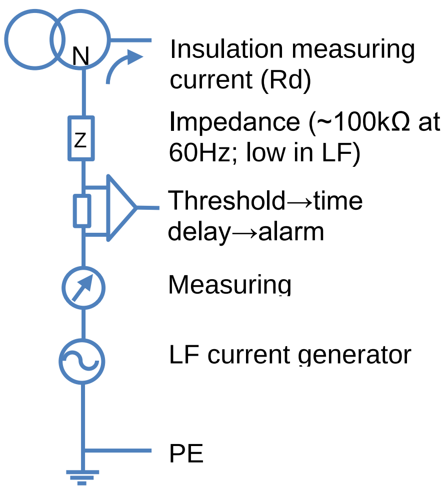


Figure 15. Insulation Monitoring Device (IMD) functional diagram

This minor disadvantage in comparison with frequency injection is compensated with an advantage of locating the first fault. Low frequency current injection elements can separately provide the network's insulation resistance and reactance. Also, they allow locating the first fault without circuit opening and without the issues due to highly capacitive feeders.

- GFLD operating method - The most typical approach is to inject an identifiable current (with a frequency different from the network frequency). The generator can be the IMD. Then, by means of magnetic current sensors (toroid transformers and/or clamp-on probe) associated with an amplifier tuned to the injected current frequency, it is possible to trace its path up to the fault (as shown in Figure 16). Alternative solution consists in comparing, constantly and for each circuit, the value of its resistance with a pre-set or programmable threshold value.

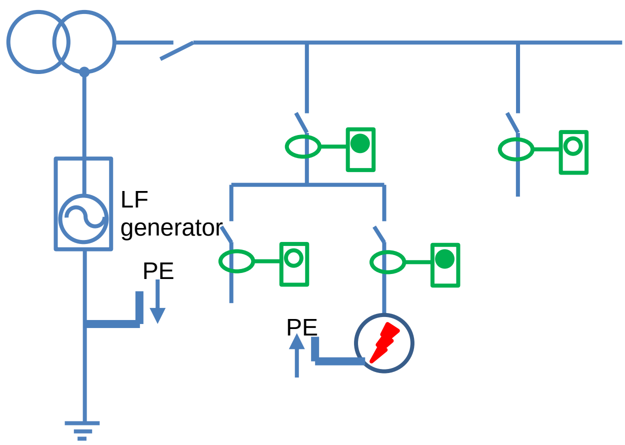


Figure 16. Locating insulation faults by tracing the path of a low frequency current injected at the installation origin

This approach enables the following actions, both locally and remotely:

- First fault reporting (IMD)
- Locating of this fault (GFLD) in order to fix it (curative maintenance) (as shown in Figure 17)
- Information about insulation evolution in time, feeder by feeder, to take corrective action on feeders with abnormal insulation drops (predictive maintenance)

-Surge limiters are connected between a live conductor (neutral or phase) and the ground. Therefore, their arcing voltage U_e must be adapted to the assembly.

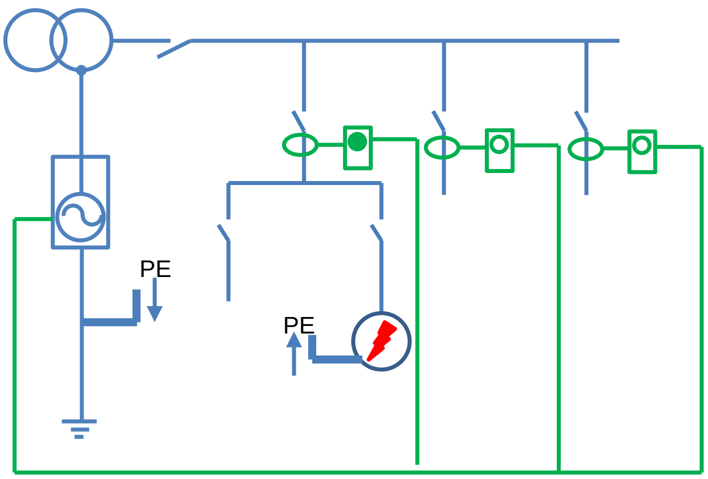


Figure 17. GFLD operating principle with low frequency impedance measurement

Therefore, there are two models for a 60 Hz network:

- 250 V for connection to the neutral
- 400 V, for connection to a phase

Their function is twofold:

- Limit voltage on the LV network on MV/LV disruptive breakdown in the distribution transformer. In this case, the limiter must flow off to ground the "residual" current of the MV network.
- Limit lightning over-voltages - This relates for their characteristics.

Neutral protection according to the system grounding

The neutral must be broken by a multi-pole device:

- In TT and TN grounding arrangements, if neutral cross-section is less than phase cross-section
- In terminal distribution in view of the Neutral/Phase reversal risk

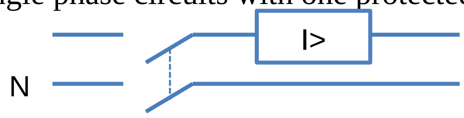
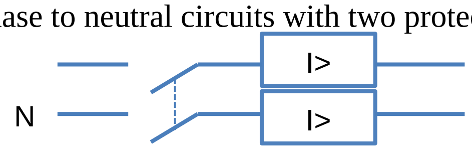
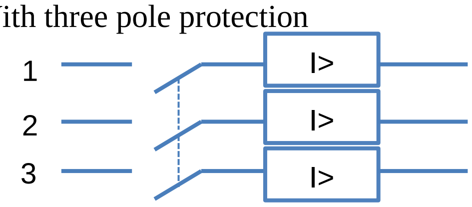
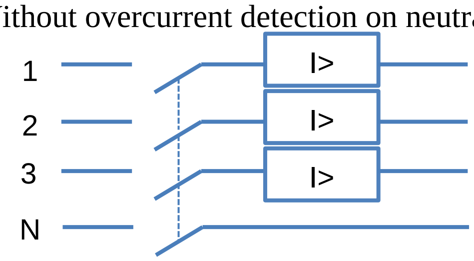
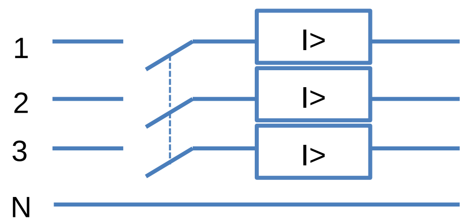
The neutral must be protected and broken:

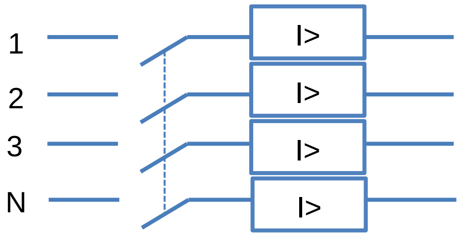
- In IT grounding systems for intervention of the protection device on the double fault, with one of the faults potentially on the neutral
- In TT and TN-S grounding systems if neutral cross-section is less than phase cross-section
- For all system grounding if the installation produces harmonic currents of rank 3 and multiples (particularly if neutral cross-section is reduced).

In TN-C the neutral, which is also the PE, cannot be broken. This is dangerous as a result of its potential variations, due to load currents and insulation fault currents. To avoid risks, a local equi-potentiality and a ground connection must be provided for each zone/consumer.

Table 9 indicates which circuit-breaker types should be used for certain grounding arrangements. Note that TT and TN grounding arrangements can use the same devices (with an additional residual current module in TT).

Table 9. Circuit breakers according to system grounding

Circuits	Diagrams			
	TN-C	TN-S	TT	IT
Single phase circuits				
Single phase circuits with one protected pole  Two pole circuit breaker (1-protected pole 2-de-energized poles)	No	Yes	Yes	No
Phase to neutral circuits with two protected poles  Two pole circuit breaker (with two protected poles)	No	Yes	Yes	Yes
Three phase circuits without neutral				
With three pole protection  Three pole circuit breaker	Yes	Yes	Yes	Yes
	TN-C	TN-S	TT	IT
Three phase circuits with neutral				
Without overcurrent detection on neutral  Four pole circuit breaker with three protected poles	No	Yes	Yes	No
	Yes	Yes	Yes	No

Three pole circuit breaker				
Three phase circuits without neutral				
With overcurrent detection on neutral  Four pole circuit breaker with four protected poles	No	Yes	Yes	Yes

Selection of system grounding

The three system grounding described and standardized by relevant regulations have optimum safety as their common objective. Regarding personnel protection, the three systems are equivalent if all installation and operating rules are complied with. Regarding the features specific to each system, none of the systems can be preferred over another. Rather, selection of system grounding needs to result from an agreement between the network user and systems designer. They need to agree on:

- Installation features
- Operating conditions and requirements

Techniques for choosing the system grounding

Three system grounding types can all be part of the same electrical installation. This provides the best possible solution to safety and availability requirements. Selection steps include:

- Checking that the choice is not specified or stipulated by standards or regulations (decrees, regulatory decisions)
- Discuss with the end user to understand his requirements and resources:
    - Requirements for continuity of service
    - Whether or not there is a maintenance service
    - Fire hazard

Typically:

- Continuity of service and maintenance service: the IT will be selected
- Continuity of service and no maintenance service: No ideal solution -It is preferred to use the TT grounding system whose discrimination on tripping is easier to

implement and which minimises damage with respect to the TN. The installation of an additional output is easily accomplished without the necessity of further calculations.

- Continuity of service not vital: it is preferred to use the TN-S (quick repairs and extensions done according to rules)
- Continuity of service not essential and no maintenance service: Prefer the TT grounding system
- Fire hazard: IT grounding system if maintenance service and use of 0.5 A RCD or TT grounding system

- Finally, here are the special characteristics of network and loads:
  - Very long network or, even more important, leakage current: it is preferred to use the TN-S grounding system
  - Use of replacement or standby power supplies: it is preferred to use the TT grounding system
  - Loads sensitive to high fault currents (motors): it is preferred to use the TT or IT grounding system
  - Loads with low natural insulation (furnaces) or with large HF filter (large computers): it is preferred to use the TN-S grounding system
  - Supply of control and monitoring systems: it is preferred to use the IT grounding system (continuity of service) or the TT grounding system (enhanced equi-potentiality of communicating devices)

Since there is no ideal choice with single system grounding, it is suggested to implement several system grounding techniques in the same installation.

References

- Technique Schneider Electric no. 172
- IEC 60241: Fuses for domestic and similar purposes
- IEC 60269: Low voltage fuses
- IEC 60364: Electrical installation of buildings
- IEC 60479: Effects of currents flowing through the human body
- IEC 60755: General rules for residual current devices
- IEC 60947-2: Low voltage switchgear 2nd part: circuit-breakers
- IEC 61008: Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCB's)
- IEC 61009: Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses (RCBO's)